KOBE–FHD–93–08
September 1993

Effects of the large gluon polarization on $xg_1^d(x)$ and J/ψ productions at polarized ep and pp collisions

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Abstract

The recent SMC data of $xg_1^d(x)$ are reproduced with the large polarized gluons. To study further the polarized gluon distribution in a proton, we calculate the spin–dependent differential cross section for J/ψ leptoproductions and the two–spin asymmetry for J/ψ hadroproductions. Its experimental implication is discussed.

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There have been several theoretical interpretations on the"proton spin crisis"[1, 2]. Among them, there is an interesting idea that gluons contribute significantly to the proton spin through the $U_A(1)$ anomaly[3]. In this description the amount of the proton spin carried by quarks is not necessarily small. The integrated value of the spin–dependent gluon($\Delta G(Q^2)$) inside a proton concomitantly becomes as large as $5 \sim 6$ at $Q_0^2 = 10.7\mathrm{GeV}^2$(EMC value).

Recently, the E581/704 collaboration at Fermilab[4] measured the two–spin asymmetries $A_{LL}^{\pi^0}(\overset{(-)}{p}p)$ for inclusive π^0–production in pp and $\overline{p}p$ collisions of longitudinally polarized beams on longitudinally polarized targets at $\sqrt{s} = 20\mathrm{GeV}$. By comparing the measured asymmetries $A_{LL}^{\pi^0}(\overset{(-)}{p}p)$ with the theoretical predictions given by Ramsey et al.[5], the E581/704 collaboration concluded that the large gluon polarization inside a proton was ruled out at 95% CL by the data. However, in recent papers [6, 7], it has been emphasized that large $\Delta G(Q^2)$ can still be consistent with the experimental data for both cases of pp and $\overline{p}p$ collisions if one adopts the spin–dependent gluon distribution function which is large for $x < 0.1$ but small for $x \geq 0.1$. In addition, Vogelsang and Weber[7] have studied the reliability of perturbative QCD predictions for $A_{LL}^{\pi^0}(\overset{(-)}{p}p)$ by taking the intrinsic k_T–smearing effects into account and concluded that the results remain still valid. Accordingly the E581/704 data do not necessarily rule out the large gluon polarization but strongly constrain the shape of the spin–dependent gluon distributions. However, is the polarized gluon contribution really so large in a proton? In order to confirm this, it is very important to measure, in experiments, physical quantities in special processes which are sensitive to the magnitude of spin–dependent gluon distribution.

In this work, we study the effect of the possible large gluon polarization in interesting processes. To examine the effect of the large gluon distribution, we take, as a typical example, our previous model[6] which has a large polarized gluon distribution,

$$\delta G(x, Q^2 = 4GeV^2) = C\ x^{0.6}(1-x)^{14} G(x, Q^2 = 4GeV^2)\ . \tag{1}$$

where a constant $C = 6.208$ is determined so as to fit the experimental integrated value of $g_1^p(x, Q^2)$, *i.e.*, $\int_0^1 g_1^p(x, Q_0^2)dx = 0.126$ (EMC data)[8]. $G(x, Q^2)$ is the spin–independent gluon

distribution function with "B$_-$" parameterization by KMRS[9]. The spin–dependent gluon distribution given by eq.(1) takes a large integrated value : $\Delta G(Q_0^2) \equiv \int_0^1 \delta G(x, Q_0^2) dx = 6.14$. In literature[2, 10], people have discussed many examples of large $\Delta G(Q_0^2)$ which also fit well to EMC $g_1^p(x)$ data. Compared with these distributions of polarized gluons, the distribution given by eq.(1) is very special since it is large for $x < 0.1$ but small for $x \geq 0.1$. In the previous work[6], we could explain satisfactorily the EMC data ($g_1^p(x)$) and the E581/704 data ($A_{LL}^{\pi^0}(\overset{(-)}{p}p)$) by using eq.(1).

Recently, the spin–dependent structure function of deutron $g_1^d(x)$ has been measured by the SMC group at CERN[11] using polarized muon beams on polarized deuteron targets. Here, to examine the large gluon polarization, we apply eq.(1) to the SMC data together with the spin–dependent quark distribution functions[12]. The results are shown in fig.1, in which one can see that the distribution eq.(1) is consistent with the SMC data even though ΔG is large. Note that we have no free parameters in calculating $g_1^d(x)$.

Now, let us get into the consideration of the physical quantities in the specific processes which are sensitive to the spin–dependent gluon distributions. In this work, we present two interesting quantities which predominantly depend on the spin–dependent gluon distributions : one is the spin–dependent differential cross section of inelastic J/ψ productions in polarized electron–polarized proton collisions and the other is the two–spin asymmetry of J/ψ productions in polarized proton–polarized proton collisions.

First, we consider the inelastic J/ψ production in polarized ep collisions *. The cross sections of this process are directly related to the distribution of polarized gluons. Since we are considering the region where the J/ψ particles are produced via the photon–gluon fusion, $\gamma^* g \rightarrow J/\psi\ g$, shown in fig.2, we take the kinematic region as[14]

$$z = \frac{p_{J/\psi} \cdot p_p}{Q \cdot p_p} < 0.8\ , \qquad \frac{p_T^2}{m_{J/\psi}^2} > 0.1\ , \tag{2}$$

where p_T is the transverse momentum of the produced J/ψ. Q, $p_{J/\psi}$ and p_p represent the

*The J/ψ productions in unpolarized ep collisions have been studied by Stirling and his collaborators[13].

four–momenta of the (virtual) photon, J/ψ and the proton, respectively. $z \to 1$ is in the elastic domain and for $p_T \to 0$ the multiple soft gluon emission must be considered. The spin–dependent differential cross section for the subprocess $\gamma^* g \to J/\psi\ g$ is

$$\begin{aligned} \frac{d\Delta\hat{\sigma}}{d\hat{t}} &\equiv \frac{1}{4}\left[\frac{d\hat{\sigma}_{++}}{d\hat{t}} - \frac{d\hat{\sigma}_{+-}}{d\hat{t}} + \frac{d\hat{\sigma}_{--}}{d\hat{t}} - \frac{d\hat{\sigma}_{-+}}{d\hat{t}}\right] \\ &= \frac{8\pi m_{J/\psi}^3 \alpha_S^2 \Gamma_{ee}}{3\alpha\ \hat{s}^2} \frac{\hat{s}^2(\hat{s}-m_{J/\psi}^2)^2 - \hat{t}^2(\hat{t}-m_{J/\psi}^2)^2 - \hat{u}^2(\hat{u}-m_{J/\psi}^2)^2}{(\hat{s}-m_{J/\psi}^2)^2(\hat{t}-m_{J/\psi}^2)^2(\hat{u}-m_{J/\psi}^2)^2}\ , \end{aligned} \tag{3}$$

where $\frac{d\hat{\sigma}_{+-}}{d\hat{t}}$, for instance, denotes that the helicity of the virtual photon is positive and that of the gluon negative, and Γ_{ee} is the leptonic decay width of J/ψ, $\Gamma_{ee} = 5.36$keV. $\hat{s}$,$\hat{t}$ and $\hat{u}$ are Mandelstam variables. At the hadron level $\gamma^* p \to J/\psi\ X$, we can calculate the differential cross section as

$$\frac{d\Delta\sigma}{d\hat{t}} = \int \delta G(x, Q^2) \frac{d\Delta\hat{\sigma}}{d\hat{t}} dx\ , \tag{4}$$

where $\delta G(x, Q^2)$ is the spin–dependent gluon distribution function. x is the fraction of the proton momentum carried by the initial state gluon and is given as

$$x = \frac{1}{s_T}\left(\frac{m_{J/\psi}^2}{z} + \frac{p_T^2}{z(1-z)}\right)\ , \tag{5}$$

where $\sqrt{s_T}$ is the total energy in photon–proton collisions. We express eq.(4) in terms of observable variables as

$$\begin{aligned} \frac{d^2\Delta\sigma}{dz dp_T^2} &= \frac{8\pi\alpha_S^2 m_{J/\psi}^3 \Gamma_{ee} z(1-z) x \delta G(x, Q^2)}{3\alpha\{m_{J/\psi}^2(1-z) + p_T^2\}^2} \\ &\times \left[\frac{1}{(m_{J/\psi}^2 + p_T^2)^2} - \frac{(1-z)^4}{\{m_{J/\psi}^2(1-z)^2 + p_T^2\}^2} - \frac{z^4 p_T^4}{(m_{J/\psi}^2 + p_T^2)^2\{m_{J/\psi}^2(1-z)^2 + p_T^2\}^2}\right]. \end{aligned} \tag{6}$$

Using $\alpha_S(m_{J/\psi}^2) = 0.4$ together with the large polarized gluon distribution eq.(1), we can estimate the spin–dependent differential cross section eq.(6). At HERA energy $\sqrt{s_T} = 185$GeV, $d^2\Delta\sigma/dzdp_T^2$ vs. p_T^2 is shown in fig.3 for various values of z. As shown in eq.(6), this distribution is directly proportional to the magnitude of the polarized gluon distribution. Therefore, by detecting it with high precision, one can get to know how large the gluon polarization is. We

hope that our present predictions would be tested in the forthcoming HERA experiments for polarized electron–polarized proton collisions.

Another interesting quantity is the x dependence of the spin–dependent differential cross section which would also be measured in the forthcoming experiments. By rewriting eq.(6), we can get

$$\frac{d\Delta\sigma}{dx} = x\delta G(x, Q^2)\delta f(x, x_{min}) \ , \tag{7}$$

with

$$\begin{aligned} \delta f(x, x_{min}) &= \frac{16\pi\alpha_S^2\Gamma_{ee}}{3\alpha m_{J/\psi}^3}\frac{x_{min}^2}{x^2} \\ &\times \left[\frac{x - x_{min}}{(x + x_{min})^2} + \frac{2x_{min}x \ln\frac{x}{x_{min}}}{(x + x_{min})^3} - \frac{x + x_{min}}{x(x - x_{min})} + \frac{2x_{min}\ln\frac{x}{x_{min}}}{(x - x_{min})^2}\right] \ , \end{aligned} \tag{8}$$

where $x_{min} \equiv m_{J/\psi}^2/s_T$. δf is a function which is sharply peaked in x just above x_{min}. A numerical calculation derives $x_{peak} = 1.53x_{min}$. Fig.4 shows the x dependence of $d\Delta\sigma/dx$ calculated using eq.(1) at various energies including relevant HERA energies. As δf has a sharp peak, the observed cross section $d\Delta\sigma/dx$ directly reflects the spin–dependent gluon distribution near x_{peak}. As is seen from eq.(7), $d\Delta\sigma/dx$ is linearly dependent on the spin–dependent gluon distribution. Thus, if $\delta G(x)$ is small or vanishing, $d\Delta\sigma/dx$ is necessarily small. We are eager for the result in fig.4 being checked in the future experiments.

Next, we discuss the two–spin asymmetry A_{LL} for inclusive J/ψ productions in polarized proton–polarized proton collisions. Since the J/ψ productions come out only via gluon–gluon fusion processes at the lowest order of QCD diagrams, this quantity is sensitive to the spin–dependent gluon distribution in a proton. Let us define the $A_{LL}^{J/\psi}(pp)$ as

$$A_{LL}^{J/\psi}(pp) = \frac{[d\sigma(p_+p_+ \to J/\psi\ X) - d\sigma(p_+p_- \to J/\psi\ X)]}{[d\sigma(p_+p_+ \to J/\psi\ X) + d\sigma(p_+p_- \to J/\psi\ X)]} = \frac{Ed\Delta\sigma/d^3p}{Ed\sigma/d^3p} \ , \tag{9}$$

where $p_+(p_-)$ denotes that the helicity of a proton is positive (negative). In eq.(9), the numerator (denominator) represents the spin–dependent (spin–independent) differential cross section

for the hard–scattering parton model and is given by

$$E\frac{d\Delta\sigma}{d^3p} = \frac{1}{\pi}\int_{x_a^{min}}^{1} dx_a \delta G(x_a,Q^2)\delta G(x_b,Q^2)\left(\frac{x_a x_b}{x_a - x_1}\right)\frac{d\Delta\hat{\sigma}}{d\hat{t}}(\hat{s},\hat{t},\hat{u}) \ , \tag{10}$$

$$E\frac{d\sigma}{d^3p} = \frac{1}{\pi}\int_{x_a^{min}}^{1} dx_a G(x_a,Q^2)G(x_b,Q^2)\left(\frac{x_a x_b}{x_a - x_1}\right)\frac{d\hat{\sigma}}{d\hat{t}}(\hat{s},\hat{t},\hat{u}) \ , \tag{11}$$

where x_a is the momentum fraction in the proton a and

$$x_1 = \frac{e^y}{\sqrt{s}}\sqrt{m_{J/\psi}^2 + p_T^2} \ , \qquad x_2 = \frac{e^{-y}}{\sqrt{s}}\sqrt{m_{J/\psi}^2 + p_T^2} \ ,$$

$$x_b = \frac{x_a x_2 s - m_{J/\psi}^2}{s(x_a - x_1)} \ , \qquad x_a^{min} = \frac{x_1 - \tau}{1 - x_2} \ .$$

Here y is the rapidity of the produced J/ψ particle and $\tau \equiv m_{J/\psi}^2/s$. As J/$\psi$ particles are produced via $gg \to J/\psi \ g$, differential cross sections of the subprocess included in eqs.(10) and (11) are formulated in the framework of perturbative QCD[15]. Then we get

$$\begin{aligned}\frac{d\Delta\hat{\sigma}}{d\hat{t}} &= \frac{5\pi\alpha_S^3(Q^2)|R(0)|^2 m_{J/\psi}}{9\ \hat{s}^2} \\ &\times \left[\frac{\hat{s}^2}{(\hat{t}-m_{J/\psi}^2)^2(\hat{u}-m_{J/\psi}^2)^2} - \frac{\hat{t}^2}{(\hat{u}-m_{J/\psi}^2)^2(\hat{s}-m_{J/\psi}^2)^2} - \frac{\hat{u}^2}{(\hat{s}-m_{J/\psi}^2)^2(\hat{t}-m_{J/\psi}^2)^2}\right] \ ,\end{aligned} \tag{12}$$

$$\begin{aligned}\frac{d\hat{\sigma}}{d\hat{t}} &= \frac{5\pi\alpha_S^3(Q^2)|R(0)|^2 m_{J/\psi}}{9\ \hat{s}^2} \\ &\times \left[\frac{\hat{s}^2}{(\hat{t}-m_{J/\psi}^2)^2(\hat{u}-m_{J/\psi}^2)^2} + \frac{\hat{t}^2}{(\hat{u}-m_{J/\psi}^2)^2(\hat{s}-m_{J/\psi}^2)^2} + \frac{\hat{u}^2}{(\hat{s}-m_{J/\psi}^2)^2(\hat{t}-m_{J/\psi}^2)^2}\right] \ ,\end{aligned} \tag{13}$$

with

$$\hat{s} = x_a x_b s \ , \quad \hat{t} = -x_a x_2 s + m_{J/\psi}^2 \ , \quad \hat{u} = -x_b x_1 s + m_{J/\psi}^2 \ ,$$

where $R(0)$ is the value of the radial S–wave function at the origin. For estimation of $A_{LL}^{J/\psi}(pp)$, we choose two different sets of the spin–dependent gluon distributions. One is the large polarized gluon distribution in eq(1). The other is the vanishing one $\delta G(x,Q_0^2) = 0$. Setting $y = 0$ with the definition $Q^2 = m_{J/\psi}^2 + p_T^2$ and using Duke–Owens parametrization (set 1) [16] as the spin–independent gluon distribution function, we plot $A_{LL}^{J/\psi}(pp)$ as a function of the transverse momenta of the J/ψ at $\sqrt{s} = 20$ and 100GeV in fig.5. We see that the large polarized gluon

distribution in the range $0 < x < 0.1$ contributes much to $A_{LL}^{J/\psi}(pp)$ at moderate p_T regions ($p_T \gtrsim 1$GeV). Note that here we do not consider the very small p_T regions ($p_T < 1$GeV) where soft gluon effects of QCD can not be neglected. For large p_T regions (for example, $p_T > 3$GeV (15GeV) for $\sqrt{s} = 20$GeV (100GeV)) the increase of $A_{LL}^{J/\psi}(pp)$ is seen even for the case of the vanishing gluon distribution, $\delta G(x, Q_0^2) = 0$, because of the Q^2 evolution of gluon distribution functions. But in these regions the $A_{LL}^{J/\psi}$ predicted with the large gluon polarization is not so significantly different from that with the vanishing one and hence we would not be able to find practically the difference between them. On the other hand, for moderate p_T regions ($p_T \gtrsim 1$GeV) the predictions for two cases are quite different and would be tested easily in experiments. Therefore we can get knowledge of ΔG by measuring $A_{LL}^{J/\psi}$ for moderate p_T regions.

In summary, we have examined the effect of the large gluon polarization on some physical quantities in special processes which are sensitive to the magnitude of gluon polarizations. By using the large polarized gluon distribution, $\Delta G(Q_0^2) = 6.14$, which is consistent with both the EMC data and the E581/704 data, we could reproduce successfully the recent SMC data of $xg_1^d(x)$ without free parameters.

Furthermore, in order to test the effects of large gluon polarizations in other processes, we have calculated, using the large polarized gluon distribution, some interesting quantities, *i.e.* $d^2\Delta\sigma/dzdp_T$ and $d\Delta\sigma/dx$ for J/ψ leptoproductions, $A_{LL}^{J/\psi}(pp)$ for J/ψ hadroproductions. Since $d^2\Delta\sigma/dzdp_T$ and $d\Delta\sigma/dx$ are directly proportional to the polarized gluon distribution, one can easily examine the magnitude of the gluon polarization by measuring these quantities in experiments. Furthermore, as for $A_{LL}^{J/\psi}(pp)$, there would be a good chance to find the large polarized gluon in moderate p_T regions ($p_T \gtrsim 1$GeV). The J/ψ productions in polarized ep and pp collisions considered here can therefore serve as a very clean probe of the polarized gluon densities in a proton. We hope these predictions would be tested in the forthcoming experiments.

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Figure captions

Fig. 1: The dependence of the spin–dependent deuteron structure function in term of $xg_1^d(x, Q^2)$ on x at $Q^2 = 4.6\mathrm{GeV}^2$. Experimental data are taken from [11].

Fig. 2: The lowest order QCD diagram for the inelastic J/ψ leptoproduction in polarized electron–polarized proton collisions.

Fig. 3: The differential cross section $d^2\Delta\sigma/dzdp_T^2$ vs. p_T^2 at $\sqrt{s_T} = 185\mathrm{GeV}$ for various values of z. The curves are predicted using the large polarized gluon distribution function eq.(1) in the inelastic domain region $p_T^2/m_{J/\psi}^2 > 0.1$. Q^2 is typically taken to be $m_{J/\psi}^2$.

Fig. 4: The distribution $d\Delta\sigma/dx$ as a function of x for different values of $\sqrt{s_T}$ is predicted using eq.(1) as the spin–dependent gluon distribution.

Fig. 5: Using $\Delta G(Q_0^2) = 6.14$ and $\Delta G(Q_0^2) = 0$, the two–spin asymmetries $A_{LL}^{J/\psi}(pp)$ for $y = 0$ (namely, $\theta = 90^\circ$ where θ is the production angle of J/ψ in the CMS of a colliding proton) calculated as a function of transverse momenta p_T of J/ψ at (a) $\sqrt{s} = 20\mathrm{GeV}$, and (b) $\sqrt{s} = 100\mathrm{GeV}$. The solid (dashed) curve corresponds to $\Delta G(Q_0^2) = 6.14$ ($\Delta G(Q_0^2) = 0$).